Next Generation Hydrogen Storage

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Objectives

- Adapt derivative technology from today's tanks to reduce cost by ~50%
- Improve performance of tanks by incorporating new high-strength materials
- Improve useable density of physical hydrogen storage through conformability
- Develop fundamental understanding of structural storage in various geometries
- Demonstrate safety innovations as components in ongoing burst experiments
- Contribute expertise to regulatory processes reflecting the results of research

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year R,D&D Plan:

- A. Cost
- B. Weight and Volume
- F. Codes and Standards
- H. Sufficient Fuel Storage for Acceptable Vehicle Range
- J. Lack of Tank Performance Data

Approach

- Gain theoretic understanding of models that combine mass, volume, and cost
- Conduct scholastic research in University libraries seeking ultra-strong materials
- Construct test equipment capable of safely burst testing small prototypes
- Develop mechanical interface that enables assembled (not wound) tanks
- Adopt Statistical Process Control and Statistical Qualification analyses
- Collect suitable data to enable statistical engineering of burst probabilities

Accomplishments

- Established fundamental new dimensionless formalism that combines mass, volume, and cost
- Performed first statistical qualification on pressure vessel structural component
- Adopted Weibull statistical distribution identification method to tank failure
- Discovered new geometries capable of carrying structure loads through replicates
- Explored new structural geometries ideal for mass production with composites

Future Directions

- Prototype new structural geometries ideal for mass production with composites
- Extend statistical methods to burst testing of small pressure vessel prototypes
- Match dimensionless theory to actual burst performance of replicated structures
- Acquire data on the unexplored tensor debonding waves in "turn to dust" bursts
- Learn to engineer tailored elasticity and self-destruction for better crash safety

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Introduction

Physical containment of hydrogen has been accomplished successfully by tanks for the past few decades. Compressed hydrogen gas at ambient temperature as a means of storing hydrogen is already available and getting better. So compressed hydrogen storage provides a near-term solution based on already-solved problems, with well understood limitations. Current and next-generation hydrogen tanks are on track to achieve the 2005 and 2010 targets in the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year R,D&D Plan. The relative absence of further technical risks in these two generations of tanks provides near-term opportunities to reduce their costs significantly by taking calculated risks on new ways to build them.

The most advanced (Type IV) hydrogen tanks built with current technology have potential cost reduction of roughly a factor of two. That potential formed the basis for planning advanced tank development experiments at LLNL. On the way to those experiments, fundamental discoveries emerged which foretell several directions for expansion of the frontiers of physical containment. Tanks are not the only structures suitable for physical storage of compressed hydrogen - some of the newly discovered containment geometries could do the same job better, providing greater range, shape-ability, and lower cost. Taking the risks required to depart from the prior art in advanced hydrogen tanks can make physical containment of hydrogen a strong contender for the 2015 Program Plan Objectives.

Approach

LLNL advanced tank development efforts followed a deliberate plan intended to reduce the cost of hydrogen storage tanks twofold. Most of those savings are expected to derive from a change in qualification methods applied after manufacture. Replacing arbitrary safety factors with real failure statistics (using a discipline called Statistical Process Control, or SPC) can save roughly 30% of costly structural mass. Such SPC is applied routinely in mass-produced high-technology products like tires and semiconductors, and its first application to tank components was made in this year's research at LLNL (illustrated in Figure 1).

The composite structural components that were tested to failure form the critical assembly interface of several new kinds of hydrogen containers (shown in Figure 2), which LLNL expects to prototype in the next fiscal year as an attractive alternative to conventional (wound composite) tanks. These new kinds of assembled tanks carry most of the structural loads through the internal volume of the container. The limitations of physical storage are no longer imposed by a highly developed prior art in advanced (wound composite) tanks, and must be replaced by

Actual Failure Data collected from assembly failure forces :

The first installment of structural testing wherein a nearly identical collection of samples is broken

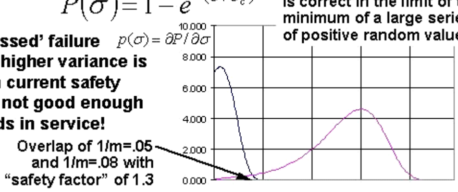
Diameter	N	material	form	Epoxy	Shear Strength
0.840"	1	composite	tube	Vendor 1	200 psi
0.450"	4	composite	rings	Vendor 1	460-870 psi
0.335"	3	Mg	discs	Vendor 2	880-1025 psi
0.335"	5	Mg	discs	Vendor 1	380-670 psi

Sample Size 'identifies' Weibull Distribution :

$$P(\sigma) = 1 - e^{-(\sigma/\sigma_c)^m}$$

The other "extreme value" distribution (vs. Gaussian) Is correct in the limit of the minimum of a large series of positive random values

Risk of 'suppressed' failure modes with higher variance is neglected in current safety standards – not good enough for thousands in service!



Recommend insurance requirements, European-required batch testing

Figure 1. Statistical Research Based on the Weibull Distribution and Real Failure Force Data

models based on raw materials structural properties and feasible, mass-producible component geometries.

Results

Attractive geometries and materials options for such non-tank hydrogen containers were the target of considerable investigation this year. Packing replicated structural components together (as illustrated in Figure 3) was found to offer statistical advantages, comparable mass, and nearly-arbitrary conformability. The versatility of shapes into which such 'macro-lattices' could be assembled provides a route to 'ultra-conformability' that could roughly halve the volume penalty of storing compressed hydrogen aboard motor vehicles.

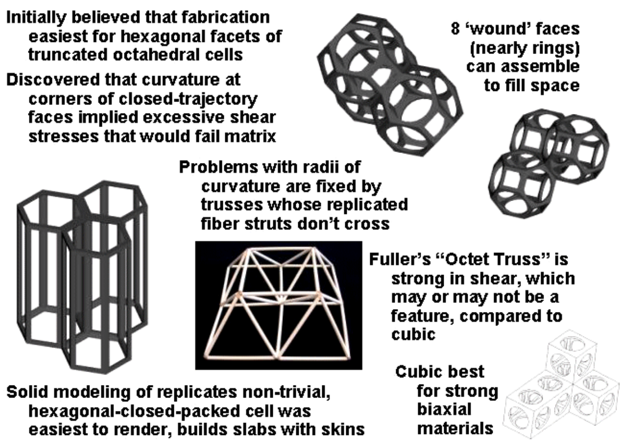


Figure 2. Various 'Non-Tank' Geometries Assemble into 'Macro-Lattices' to Enable Mass Production of Nearly-Arbitrary, Ultra-Conformable Shapes

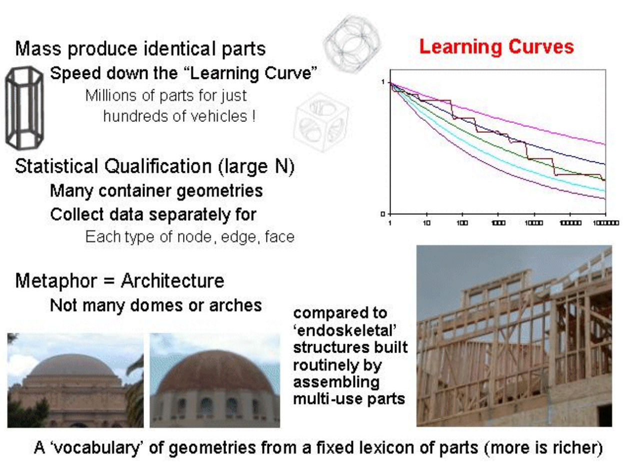


Figure 3. Mass Production Advantages of Macrolattices, Including a Metaphor to Architectural Structures

The mass and volume of tanks and non-tanks can be modeled as feasible-technology curves in a volume vs. mass plot (shown in Figure 4). A fundamental theoretical innovation was developed to enable calculation of the performance consequences of novel non-tank geometries. Its formulae allow designers to trade off mass, volume, and cost, while constraining vehicle range, proceeding with full rigor to combine dissimilar dimensioned performance measures. Figure 4 (volumetric vs. mass density of hydrogen storage) forecasts that progress will follow calculable paths to the right of the 2005 and 2010 objectives of DOE's Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year R,D&D Plan.

Conclusions

- The frontier of performance for physical hydrogen storage has been re-opened.
- Statistical Process Research has been initially demonstrated for hydrogen storage.
- Statistical methods can limit probabilities of failure to required levels (Pfail<10^{-7}).
- Mass production and innovative non-tank structures can provide copious statistics.

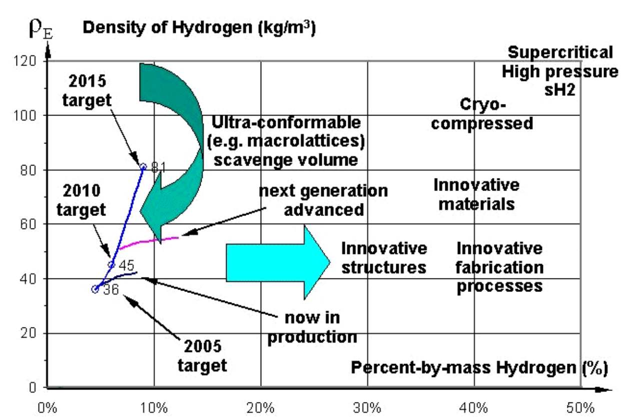


Figure 4. Advanced Type IV Pressure Vessels on Track for Hydrogen Storage Objectives - With Lots of Room for Progress

FY 2003 Publications/Presentations

1. Hydrogen Storage Using Light Weight Tanks, DOE Annual Hydrogen Fuel Cells and Infrastructure Program Review, Berkeley, CA, May 20, 2003.